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A DESI DR1 Radial-Velocity Search for Dark Compact Companions: A Strong but Unconfirmed Candidate Around a dM0 Star

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ABSTRACT

We present a conservative, fully reproducible search for radial-velocity (RV) variability in the public Dark Energy Spectroscopic Instrument (DESI) Data Release 1 (DR1) Milky Way Survey. Using only per-epoch RV measurements, we identify stars whose velocity variability is both highly significant and robust under leave-one-out tests. A "negative space" validation pipeline then rejects ordinary luminous companions using Gaia DR3 astrometry, WISE infrared photometry, GALEX ultraviolet imaging, TESS and ZTF time-domain photometry, deep Legacy Survey imaging, and archival X-ray and radio catalogs.

One system, Gaia DR3 3802130935635096832 (DESI TargetID 39627745210139276), emerges as the most extreme survivor. DESI provides four RV epochs spanning 38.9 days with a maximum RV span $\Delta\mathrm{RV}_{\mathrm{max}} \approx 146$ km s^{-1}. A constant-RV model is rejected at $\Delta\chi^2 \approx 2.7 \times 10^4$ (DESI-only), and the variability remains highly significant under leave-one-out tests.

A key forensic update is that Gaia DR3 resolves a neighbor at $\rho \simeq 0.69''$ with $\Delta G \simeq 2.21$ mag, implying a G-band flux ratio $b_G \simeq 0.13$. We perform blend-aware remeasurement of the DESI spectra using two PHOENIX templates and physically motivated flux-ratio priors; the large RV swing persists across these remeasurements. However, a persistent arm-split discrepancy between DESI R and Z arm RV estimates indicates wavelength-dependent systematics that prevent a definitive dynamical mass claim from public data alone.

Finally, we verify Gaia astrometric quality metrics via a direct query to `gaiadr3.gaia_source` (script: `scripts/verify_gaia_metrics.py`), finding RUWE = 1.954 and astrometric excess noise $\epsilon_{\mathrm{AEN}} = 0.90$ mas (16.5σ significant) at $G = 17.273$. These values indicate a poor single-source astrometric fit consistent with unresolved astrometric complexity (orbital motion and/or duplicity), but are not uniquely diagnostic given the resolved neighbor. We classify Gaia DR3 3802130935635096832 as a *strong but unconfirmed* dark compact companion candidate.

Keywords: Radial velocity(1332) — Compact objects(288) — M dwarfs(982) — Spectroscopy(1558)

1. INTRODUCTION

Quiescent compact objects—white dwarfs (WDs), neutron stars (NSs), and stellar-mass black holes (BHs)—are expected to be abundant in the Milky Way but are difficult to detect when not accreting or otherwise luminous. Radial velocities provide a purely gravitational discovery channel: a compact companion can induce large reflex motion in an ordinary star while contributing negligible light. Modern multi-epoch spectroscopic surveys are therefore natural hunting grounds for unseen companions.

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DESI DR1 provides per-epoch RVs for millions of stars in the Milky Way Survey. While DESI was not designed as a time-domain survey, the combination of multi-epoch coverage, high spectral resolution, and uniform data processing enables a systematic search for RV outliers. In this work we:

1. define conservative RV-variability metrics that are robust to outliers;

2. scan the DESI DR1 Milky Way Survey for high-significance RV variables;

3. apply a multi-wavelength "negative space" filter that searches for *gravity without light*;
4. perform targeted orbital and forensic analyses of the strongest surviving candidate, including blend-aware remeasurement and wavelength-split stress tests designed to break false positives.

All analysis scripts, configuration files, and machine-readable products are publicly available.

2. DATA SETS

2.1. *DESI DR1 Milky Way Survey*

We use per-epoch DESI DR1 Milky Way Survey RVs from the `main-bright` and `main-dark` programs. For each epoch we extract:

- heliocentric radial velocity RV_i (in km s^{-1});
- formal RV uncertainty $\sigma_{\mathrm{RV},i}$ (in km s^{-1});
- modified Julian date t_i (in days);
- DESI `TARGETID`;
- Gaia DR3 `SOURCE_ID` when available.

2.2. *LAMOST archival spectroscopy*

We identify two public LAMOST spectra (ObsIDs 437513049 and 870813030) of the target. These spectra robustly support an early-M dwarf classification for the dominant light source. However, independent RV remeasurement of these spectra is internally inconsistent across methods (FITS-header values vs CCF refits and wavelength-split CCF), so we treat LAMOST RVs as *non-decisive* for orbit fitting in this work. We retain LAMOST as the primary spectral-type constraint and as a qualitative sanity check only.

2.3. *Gaia DR3 astrometry and duplicity*

From Gaia DR3 we use: parallax and proper motions; renormalized unit weight error (RUWE); astrometric excess noise (AEN); and image-parameter-determination (IPD) summary statistics.

We verify the key Gaia DR3 quality metrics via a direct `astroquery.gaia` query to `gaiadr3.gaia_source` (script: `scripts/verify_gaia_metrics.py`). The verified values are:

Table 1. Verified Gaia DR3 astrometric metrics for Gaia DR3 3802130935635096832.

Quantity	Value
Gaia G magnitude	17.273
Parallax ϖ (mas)	0.12 ± 0.16
RUWE	1.954
Astrometric excess noise ϵ_{AEN} (mas)	0.90
AEN significance ($\epsilon_{\mathrm{AEN}}/\sigma_\epsilon$)	16.5

An elevated RUWE (commonly RUWE $\gtrsim 1.4$) indicates a poor fit of the 5-parameter single-source astrometric model and is often associated with unresolved binaries, blends, or other astrometric complexity. The parallax is poorly constrained and we therefore do not adopt a Gaia-only geometric distance.

A major forensic update is that Gaia DR3 resolves a close neighbor at a separation $\rho \simeq 0.688''$ with $\Delta G \simeq 2.21$ mag. This neighbor lies within the DESI $1.5''$ fiber aperture and must be treated as a potential blend contaminant.

2.4. *Additional surveys*

The multi-wavelength validation makes use of: WISE/2MASS photometry; GALEX NUV imaging; TESS full-frame-image photometry; ZTF multi-year g, r photometry; Legacy Survey (DECaLS/MzLS/BASS) imaging cutouts; ROSAT, XMM-Newton, Chandra X-ray catalogs; and NVSS, FIRST, and VLASS radio surveys.

3. RV VARIABILITY METRICS

3.1. *Single-target RV statistics*

For each target with N RV epochs we define the maximum observed RV span

$$\Delta\mathrm{RV}_{\max} = \max_i\left(\mathrm{RV}_i\right) - \min_i\left(\mathrm{RV}_i\right). \qquad (1)$$

Table 2. Definitions for Equation (1).

Symbol	Meaning
RV_i	Radial velocity at epoch i (km s^{-1})
$\Delta\mathrm{RV}_{\max}$	Maximum RV span across all epochs (km s^{-1})
$\max_i(\cdot)$	Maximum over epochs indexed by i
$\min_i(\cdot)$	Minimum over epochs indexed by i

To quantify the significance of the variability we define

$$S = \frac{\Delta\mathrm{RV}_{\max}}{\sqrt{\sum_{i=1}^{N}\sigma_{\mathrm{RV},i}^2}}. \qquad (2)$$

Table 3. Definitions for Equation (2).

Symbol	Meaning
S	Global RV-variability significance (dimensionless)
$\Delta\mathrm{RV}_{\max}$	Maximum RV span (km s^{-1})
$\sigma_{\mathrm{RV},i}$	Formal RV uncertainty at epoch i (km s^{-1})
N	Number of RV epochs
i	Epoch index

3.2. *Leave-one-out robustness and leverage*

We compute a leave-one-out significance $S^{(-k)}$ by excluding epoch k and recomputing Equation (2). We then define

$$S_{\min,\mathrm{LOO}} = \min_{1\le k\le N} S^{(-k)}, \qquad S_{\mathrm{robust}} = \min\left(S,\, S_{\min,\mathrm{LOO}}\right). \tag{3}$$

Table 4. Definitions for Equation (3).

Symbol	Meaning
$S^{(-k)}$	Significance S recomputed with epoch k removed
k	Index of the excluded epoch
$S_{\min,\mathrm{LOO}}$	Minimum of $S^{(-k)}$ over all excluded epochs
S_{robust}	Conservative significance statistic used for selection
S	As in Equation (2)
N	Number of RV epochs
$\min(\cdot)$	Minimum operator

We also define a leverage statistic

$$d_i = \frac{\left|\mathrm{RV}_i - \overline{\mathrm{RV}}\right|}{\sigma_{\mathrm{RV},i}}, \qquad d_{\max} = \max_i d_i, \tag{4}$$

with $\overline{\mathrm{RV}}$ the inverse-variance-weighted mean velocity.

4. NEGATIVE-SPACE VALIDATION PIPELINE

For each RV-variable candidate we apply a multi-wavelength filter designed to select systems with strong gravitational evidence for a companion but little or no corresponding light from that companion. The key checks are:

1. **Gaia astrometry and duplicity:** RUWE, AEN, and IPD statistics, plus explicit neighbor searches for Gaia-resolved companions.

Table 5. Definitions for Equation (4).

Symbol	Meaning
d_i	Leverage of epoch i (dimensionless)
$d_{\max}$	Maximum leverage over epochs i
RV_i	RV at epoch i (km s^{-1})
$\overline{\mathrm{RV}}$	Inverse-variance-weighted mean RV (km s^{-1})
$\sigma_{\mathrm{RV},i}$	RV uncertainty at epoch i (km s^{-1})
$\lvert\cdot\rvert$	Absolute value
$\max_i(\cdot)$	Maximum over epochs indexed by i

2. **WISE infrared colours:** $W1 - W2 < 0.1$ to exclude strong IR-excess systems dominated by cool luminous companions.

3. **GALEX NUV:** non-detection to exclude hot WD signatures.

4. **TESS and ZTF photometry:** no deep eclipses, no large-amplitude ellipsoidal modulation, and no strong rotation signal at the candidate orbital period family.

5. **Legacy Survey imaging:** PSF morphology and residuals to identify blends and background contaminants.

6. **X-ray and radio catalogs:** search for accreting NS/BH signatures; non-detections are converted into luminosity upper limits.

Only one object, Gaia DR3 3802130935635096832, survives all cuts and is subjected to the detailed analysis below.

5. GAIA DR3 3802130935635096832

5.1. *DESI radial-velocity data set*

Table 6 lists the DESI DR1 per-epoch RV measurements.

Table 6. DESI DR1 per-epoch RV measurements for Gaia DR3 3802130935635096832.

Epoch	Source	MJD	Date (UT)	RV $\pm\sigma_{\mathrm{RV}}$ (km s^{-1})
1	DESI	59568.488	2021-12-20	-86.39 ± 0.55
2	DESI	59605.380	2022-01-26	$+59.68 \pm 0.83$
3	DESI	59607.374	2022-01-28	$+26.43 \pm 1.06$
4	DESI	59607.389	2022-01-28	$+25.16 \pm 1.11$

The maximum DESI-only RV span is $\Delta\mathrm{RV}_{\max} = 146.07$ km s^{-1} over 38.9 days. Applying Equations (2)–(4) yields: $S \approx 79.8$ (DESI-only); $S_{\min,\mathrm{LOO}} \approx 19.8$ (DESI-only); $S_{\mathrm{robust}} \approx 19.8$ (DESI-only); $d_{\max} \approx 113$ (high-leverage epoch at -86.39 km s^{-1}).

A constant-RV fit to the DESI epochs yields $\chi^2_{\mathrm{const}} \approx 2.73\times10^4$ for three degrees of freedom, i.e. a catastrophic rejection of the constant-RV hypothesis.

5.2. *Resolved neighbor and blend parameters*

Gaia DR3 resolves a neighbor at $\rho \simeq 0.688''$ with $\Delta G \simeq 2.21$. We convert the magnitude difference into a G-band flux ratio via

$$b_G = 10^{-0.4\,\Delta G}. \tag{5}$$

Table 7. Definitions for Equation (5).

Symbol	Meaning
b_G	Flux ratio in the Gaia G band (neighbor flux / primary flux)
ΔG	Gaia G-band magnitude difference (neighbor minus primary; mag)
$10^{(\cdot)}$	Base-10 exponential function
0.4	Conversion factor between magnitudes and $\log_{10}$ flux

With $\Delta G \simeq 2.21$, we obtain $b_G \simeq 0.13$.

Because the DESI fiber diameter is $1.5''$, both sources are plausibly within the fiber. Moreover, the flux ratio is wavelength-dependent. PHOENIX-based SED estimates imply a smaller fraction in the DESI R arm and a larger fraction in the DESI Z arm, with representative values $b_R \sim 0.10$–0.11 and $b_Z \sim 0.19$–0.23 for late-M neighbors.

5.3. *Why flux dilution alone cannot create a 146 km s^{-1} swing*

If an RV extractor behaved like a linear flux-weighted centroid of two spectra, the measured RV would be bounded by a flux-weighted average. In the small-b limit, the maximum blend-induced bias scales approximately as

$$|\Delta\mathrm{RV}_{\mathrm{blend}}| \lesssim b\,|\mathrm{RV}_2 - \mathrm{RV}_1|\,. \tag{6}$$

Thus, even a large component velocity separation of $|\mathrm{RV}_2 - \mathrm{RV}_1| \sim 200$ km s^{-1} would imply $|\Delta\mathrm{RV}_{\mathrm{blend}}| \sim 26$ km s^{-1} for $b \simeq 0.13$.

Table 8. Definitions for Equation (6).

Symbol	Meaning
$\|\Delta\mathrm{RV}_{\mathrm{blend}}\|$	Magnitude of blend-induced RV bias (km s^{-1})
b	Flux ratio (neighbor flux / primary flux; dimensionless)
RV_1	Primary component RV (km s^{-1})
RV_2	Neighbor/secondary component RV (km s^{-1})
$\|\cdot\|$	Absolute value
$\lesssim$	"Less than or approximately equal to"

This bound does *not* rule out more pathological failure modes (e.g. a pipeline locking onto different spectral components at different epochs, or wavelength-dependent template mismatch), so we explicitly test those cases below using blend-aware remeasurement and arm/feature "truth filters."

6. FORENSIC TRUTH FILTERING: BLEND-AWARE REMEASUREMENT AND ARM/FEATURE CHECKS

6.1. *Blend-aware DESI remeasurement*

We re-fit the DESI spectra using PHOENIX templates for an early-M primary and a late-M neighbor, performing χ^2 minimization with inverse-variance weights and a physically motivated prior on the flux ratio informed by ΔG and SED-based b_R, b_Z expectations. Across reasonable choices of primary/neighbor templates and fixed blend fractions ($b \in \{0.05, 0.13, 0.20\}$), the inferred combined-arm RV swing remains ~ 142 km s^{-1}, consistent with the catalog swing. This indicates that the large RV excursion is not an obvious artifact of neglecting a $\sim 13\%$ contaminant.

However, model-comparison statistics (e.g. ΔBIC) can strongly favor two-component fits even when b is fixed to unrealistically small values. Because reduced chi-squared values remain $\chi^2_\nu \gg 1$ in many fits, we interpret such preferences as being driven primarily by template mismatch (i.e. model misspecification), not as decisive evidence that blending explains the RV variability.

6.2. *Arm-split consistency*

As an internal consistency check we estimate RVs separately in the DESI R and Z arms. We define an arm-split diagnostic

$$\delta_{RZ} = \mathrm{RV}_R - \mathrm{RV}_Z, \tag{7}$$

where RV_R and RV_Z are the arm-specific RV estimates.

Table 9. Definitions for Equation (7).

Symbol	Meaning
δ_{RZ}	R–Z arm RV difference (km s^{-1})
RV_R	RV estimated from the DESI R arm (km s^{-1})
RV_Z	RV estimated from the DESI Z arm (km s^{-1})

Using the available DESI arm-level products, we find arm-split differences of order tens of km s^{-1} for multiple epochs, including an epoch with $|\delta_{RZ}| \sim 36$ km s^{-1}. We do not have access to per-exposure (non-coadded) arm spectra in the present environment, so we cannot test whether this discrepancy is driven by a single exposure; we therefore treat the arm-split pathology as a serious systematic that prevents a definitive dynamical interpretation without higher-resolution follow-up.

6.3. *Feature-level RV checks*

We perform a feature-level RV sanity check by measuring shifts in prominent molecular/atomic regions (e.g. TiO and the Ca II triplet). These checks recover a large inter-epoch velocity shift of order ~ 100 km s^{-1} between the most extreme epochs, qualitatively consistent with the catalog-scale variability and inconsistent with the idea that the entire swing is a pure pipeline artifact. However, the feature-level results vary by band/feature and are therefore treated as corroborating diagnostics rather than definitive RVs.

6.4. *Gaia control-sample context*

To contextualize Gaia duplicity metrics at comparable magnitude and color, we compare the target to a Gaia DR3 control sample matched in G and $BP - RP$ (sample size $N \simeq 581$). In this control sample, the target lies at approximately the 97th percentile in RUWE and the 96th percentile in astrometric excess noise, i.e. it is an astrometric outlier consistent with duplicity or other astrometric complexity. We emphasize that this is supporting evidence rather than a unique proof, especially given the resolved neighbor.

7. PRIMARY-STAR CHARACTERIZATION

Using LAMOST spectral typing and photometry we estimate:

- effective temperature $T_{\mathrm{eff}} \simeq 3850$–$4050$ K;
- surface gravity $\log g \simeq 4.5$;
- metallicity consistent with solar within ± 0.3 dex;
- stellar mass $M_1 \approx 0.56 \pm 0.06$ M$_\odot$;
- radius $R_1 \approx 0.56 \pm 0.05$ R$_\odot$.

Because the system is a known blend at the $\sim$ 10–20% level (band-dependent), these stellar parameters should be regarded as referring to the dominant-light component and may carry additional systematic uncertainty.

8. DYNAMICAL INTERPRETATION (CONSERVATIVE BOUNDS)

The DESI-only RV span implies a minimum semi-amplitude

$$K_{\min} = \frac{\Delta \mathrm{RV}_{\max}}{2}, \tag{8}$$

so that $K_{\min} \approx 73$ km s^{-1}.

Table 10. Definitions for Equation (8).

Symbol	Meaning
$K_{\min}$	Minimum implied RV semi-amplitude (km s^{-1})
$\Delta\mathrm{RV}_{\max}$	Maximum RV span (km s^{-1})
2	Numerical factor converting peak-to-peak span to semi-amplitude

Assuming a circular orbit and adopting $K = K_{\min}$, the mass function is bounded by

$$f_{\min}(M) = \frac{P\,K_{\min}^3}{2\pi G}, \tag{9}$$

where P is the orbital period and G is Newton's gravitational constant.

Table 11. Definitions for Equation (9).

Symbol	Meaning
$f_{\min}(M)$	Lower bound on the RV mass function (in solar-mass units if P and $K_{\min}$ are in consi
P	Orbital period (time units)
$K_{\min}$	Minimum RV semi-amplitude (km s^{-1})
G	Newton's gravitational constant
π	The constant pi

For illustrative periods of order tens of days, $f_{\min}(M)$ is of order unity, implying that a NS-mass companion is plausible for edge-on geometries. Importantly, if the sampling did not capture the true extrema, then $K > K_{\min}$ and the implied mass function increases rapidly as K^3.

9. PHOTOMETRIC, X-RAY, AND RADIO CONSTRAINTS

TESS full-frame data show no deep eclipses or large coherent modulation at the candidate period family. ZTF g, r light curves show amplitudes below ~ 25 mmag at representative periods, disfavoring starspot-driven RV signals at the ~ 70 km s^{-1} level.

No counterparts are found in major X-ray or radio catalogs at useful depths. These non-detections are consistent with a detached system containing a non-interacting compact object, but are not uniquely diagnostic.

10. LIMITATIONS

Several limitations prevent a definitive claim:

1. **Sparse RV sampling.** DESI provides four epochs (two nearly simultaneous). This is sufficient to prove strong variability but not to uniquely determine the orbit.
2. **Resolved neighbor / blending.** A Gaia-resolved neighbor at $\rho \simeq 0.69''$ contaminates the DESI fiber at the $\sim$ 10–20% level depending on wavelength.
3. **Arm-dependent systematics.** Arm-split RV differences of order tens of km s^{-1} indicate a wavelength-dependent pathology that remains unresolved with public products alone.
4. **LAMOST RV instability.** LAMOST spectra support the dM0 typing, but independent RV confirmation from LAMOST is inconclusive due to internal inconsistencies across RV extraction methods.
5. **Gaia astrometric non-uniqueness.** RUWE and AEN are elevated and strongly suggest astrometric complexity, but are not uniquely attributable to orbital motion given the resolved neighbor.

11. CONCLUSIONS

We have built and stress-tested a public, scripted pipeline for identifying RV variables with unseen companions in DESI DR1. Gaia DR3 3802130935635096832 is an extreme DESI RV variable with $\Delta\mathrm{RV}_{\mathrm{max}} \approx 146$ km s^{-1} and a strong "darkness" profile. A Gaia-resolved neighbor at $\rho \simeq 0.69''$ is real and must be accounted for; blend-aware DESI remeasurement shows that the large RV swing persists and cannot be trivially attributed to a $\sim 13\%$ contaminant. Gaia DR3 quality metrics are independently verified (RUWE $= 1.954$; $\epsilon_{\mathrm{AEN}} = 0.90$ mas at 16.5σ), indicating a poor single-source astrometric fit consistent with unresolved astrometric complexity.

However, significant wavelength-dependent systematics (arm-split discrepancies of order tens of km s^{-1}) remain a serious obstacle to converting the public RVs into a definitive dynamical companion-mass claim. We therefore classify Gaia DR3 3802130935635096832 as a *strong but unconfirmed* dark compact companion candidate. The most efficient next step is high-resolution spectroscopy with spatial discrimination of the two components.

12. DATA AND CODE AVAILABILITY

All scripts, configuration files, diagnostic plots, and machine-readable results used in this work are publicly available at https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH.

Software: TESS, ZTF, DESI DR1, Gaia DR3, LAMOST

Facilities: DESI, Gaia, LAMOST, TESS, ZTF